Hydrological problems and solutions of a small island state in warm humid regions: case of Singapore

A. RAHMAN
Geography Department, National University of Singapore, Kent Ridge, Singapore 0511

Abstract Singapore with its available physical resources and the level of material affluence implies accelerated pace of urbanization. This development accompanies a myriad of hydrological problems including; availability of fresh water for a population growing in number as well as (material) affluence, disposal of storm water to prevent flooding, and disposal of waste to prevent pollution of (fresh) water bodies. This paper highlights these hydrological problems and summarizes the solutions that have successfully been implemented. The paper also identifies the role of agencies and personnel involved in the solution of the above hydrological problems.

INTRODUCTION

Singapore is a small island state very near the equator (approximate longitude 104°E, latitude 1°N. The area of its main island where over three million people live is around 600 km². Its climate throughout its space and time is warm and humid. Singapore, with its per capita GDP of over US$12 000 is cited as an example of rapid economic development and prosperity which also implies accelerated pace of urbanization and industrialization. This development accompanies a myriad of hydrological problems including; (a) availability of fresh water for a population which is growing in number as well as material affluence, (b) disposal of storm water to prevent flooding, and, (c) disposal of waste to prevent pollution of (fresh) water bodies. This paper highlights these hydrological problems and summarizes the solutions that have successfully been implemented.

FRESH WATER SUPPLY

Water use

The trends of Singapore's population increase and water consumption during the recent decades as shown in Table 1 clearly indicate that while the rate of population increase has decreased over three times the rate for water consumption has more than doubled (Kwok, 1986). The drastic decrease in population growth rate and increase in water consumption took place in the mid-70s when Singapore took pronounced leaps in technological/economic development. The Public Utilities Board of Singapore (PUB), which is responsible for development and supply of (fresh) water to the nation, sold
Table 1 Increases in Singapore's population and water consumption during three recent decades.

<table>
<thead>
<tr>
<th>Years</th>
<th>Increase in population</th>
<th>Increase in water consumption (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955-1965</td>
<td>600 000</td>
<td>120 000</td>
</tr>
<tr>
<td>1965-1975</td>
<td>500 000</td>
<td>130 000</td>
</tr>
<tr>
<td>1975-1985</td>
<td>150 000</td>
<td>290 000</td>
</tr>
</tbody>
</table>

Source: Kwok (1986)

322.8 million cubic metres of water in Singapore during 1990; 59% of this amount to domestic consumers, 32% to commercial and industrial users and 9% to others (Public Utilities Board, 1974-1990). According to the various PUB publications there has been a 3 to 4% increase in water consumption during the last decade and water consumption is expected to increase at an annual rate of 3% over the next decade (Wong & Tng, 1988). Per capita consumption during the past few years has been around 300 l day$^{-1}$.

Existing water resources

The average yearly rainfall in Singapore is around 2.4 m (Meteorological Services, 1991). Two-thirds of this amount is the yearly potential evapotranspiration (Ho, 1975). While the built-up areas (over 45% of the main Singapore island, in 1982) are continuously increasing, vegetated areas including the wooded watersheds (around 10% of the main island in 1982) are decreasing (Gupta, 1987). According to "Singapore's Green Plan" (Ministry of the Environment, 1991), about 5% of the existing land are reserved as protected catchments and another 36.3% of the land is retained as unprotected water catchment areas. The land use in these unprotected catchments is strictly controlled to be of a less polluting nature. Due to the nature of its geology, there are no groundwater resources in Singapore (Pfeiffer, 1975). Throughout its recent history, Singapore has constantly been striving to increase its own sources of fresh water supply, but given the use, physical environment and technological and economic level it became evident that this small island state could not be self sufficient in its water resources and water had to be imported (starting formally since 1932) from neighbouring countries; mainly from the southern state of Johore in Malaysia (Public Utilities Board, 1985a,b). At the same time there have been various attempts at reducing demand for fresh water. The various sources of water and various means of reducing demand are listed in Table 2.

Almost all the national water resources are confined to impounded reservoirs/lakes (total of fourteen in the country). Water from these reservoirs is subjected to (purification) treatment (total of five treatment plants in the country) and stored in service reservoirs (total of 11 such reservoirs) before being supplied to the consumers (Public Utilities Board, 1985b). The entire population of Singapore is supplied with piped water to their homes meeting the WHO standard of quality. The existing reservoirs have historically developed in more or less the same order as listed in Table 2. The oldest, first generation of reservoirs have forested catchments. Various types of agricultural activities, such as pig farming, have either been relocated or/and phased
Table 2 Alternatives for balancing supply and demand for water resources in Singapore.

<table>
<thead>
<tr>
<th>Increasing supply</th>
<th>Reducing demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing water resources</strong></td>
<td>1. Legislation</td>
</tr>
<tr>
<td>1. Reservoirs within Singapore</td>
<td>2. Price elasticity</td>
</tr>
<tr>
<td>(i) Central/Older catchments (MacRitchie, Lower Pierce, Seletar, Upper Pierce)</td>
<td>3. Metering</td>
</tr>
<tr>
<td>(ii) Estuarine catchments (Kranji, Murai, Poyan, Sarimbun, Tengah, Sungei Seletar)</td>
<td>4. Pressure reduction</td>
</tr>
<tr>
<td>(iii) Semi-urban and urban catchments (Pandan, Bedok, Jurong Lake)</td>
<td></td>
</tr>
<tr>
<td>2. Water from Johore, Malaysia</td>
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<tr>
<td>3. Recycling of waste water</td>
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</tbody>
</table>

**Potential/probable resources**

| 1. Catchments/reservoirs additions | 5. Water conservation (through educational campaigns, etc.) |
| (i) Increasing capacity of existing reservoirs | |
| (ii) Impounding new reservoirs (urban, on outer islands) | |
| 2. Additional water from neighbouring countries | |
| (i) From Malaysia | |
| (ii) From Indonesia | |
| 3. Greater recycling | |
| 4. Increase efficiency | |
| (i) Eliminate leakage | |
| (ii) System maintenance | |
| 5. Desalination | |
| 6. Others | |
| (i) Rainwater cisterns/harvesting | |
| (ii) Underground reservoirs | |
| (iii) Damming areas between islands | |


out to preserve the quality of water in reservoirs that were subsequently developed. Due to the lack of vegetated catchment areas, the recent trend is towards urban catchments which require special consideration for water collection (collecting water in reservoirs only when discharge exceeds a certain value) and treatment (e.g. disinfection using ozone instead of chlorine) to safeguard its quality. Water in all these reservoirs would supply only a small proportion of the total national demand for fresh water. According to Tan (1983) the total storage capacity of all these reservoirs is a little over 128 million cubic metres (Lower Pierce being the smallest having 2.8 and upper Pierce being the largest having 27.8 million cubic metres). According to Ho (1975) between 70 to 80% of the water consumed in Singapore during 1964-1974 was imported. This trend may not have changed much.

**Potential and probable water resources**

Potential and probable water resources are also listed in Table 2. They are considered or implemented to various degrees. Enlarging existing reservoirs has physical, technical and economic limitations. Competing land use also precludes establishing new reservoirs. With successful operation of urban reservoirs more such reservoirs may be established in the future. The total land area of Singapore utilized for water
catchment increased from 11% in 1970 to 50% in 1985 and there are plans for this to be extended to 75% (Kwok, 1986). Treating water as any other resources and importing it from neighbouring countries has been popular and would stay that way. Recycled water is currently sold to industry and used by the Parks and Recreation Department. With time the amount should increase. Efficiency of water supply in recent times has greatly improved. Very few countries could boast a of more efficient system. Desalination remains a very viable solution for augmenting the nation’s freshwater supply but as long as alternate sources are available at a very much lower cost, desalination is not an economically feasible solution. Many other schemes and proposals, as listed in Table 2, have been studied but for various reasons not implemented.

Reducing demand

Aside from continuous attempts at increasing supplies, there have been active attempts, and often implemented successfully, at reducing the demand for fresh water through various means. Several times during the recent history, appeals to save water during droughts brought down consumption by 10 to 20% (in the early 70s and 60s respectively) (Ho, 1975; Kwok, 1986). Table 2 lists some of the measures being successfully tried. For instance, the Water Supply Regulations were revised in 1983 to curb the water wastage in public places, which resulted in considerable reduction in water usage (PUB, 1985a). This was the result of the efforts of the Water Conservation Unit which was established in 1981 (Khor, 1989). Tax incentives are provided to commercial users for water conservation. With the introduction of higher water tariffs for increasing use the total consumption of water decreased. These rates are constantly being revised. For instance the current domestic rates are S$0.53, S$0.75 and S$1.10 per cubic metre for consumption blocks of 1-20, 20-40 and over 40 m³. The non domestic rate is S$1.10 per cubic metre (PUB, 1974-1990). Pressure reduction (by installing brass discs with a hole in the centre) resulted in 5% reduction in household water use (Mirror, 1983).

FLOODS

General

Singapore has had a long history of flooding. Published reports of floods go back over a century (Rahman, 1985). The continued occurrence of floods in Singapore has also resulted in greater public awareness and thus greater attention focused on this problem. While increasing urbanization increases the extent of flood-prone areas, greater concern and attention paid to minimizing the effects of flooding decreases such areas.

Causes

Both natural and anthropogenic factors may be cited as the major causes of flooding in Singapore. Among the natural factors, the nature of rainfall (high intensity and
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amounts), unfavourable physiography (first order streams or drains on steep/steeper slopes leading to major drains flowing over very gentle gradients (Gupta, 1982)), tidal influences (temporal coincidence of high tides with heavy storms preventing the water from major drains in low-lying areas from discharging into the surrounding ocean) may be considered as major causes. Thus there is a higher frequency of floods during the northeast monsoon period (November to January), and in valleys of major streams (e.g. areas surrounding the Bukit Timah canal) specially in their lower reaches (e.g. around Newton Circus area) (Foo, 1986). Modification of near-surface and surficial ground characteristics provide the major anthropogenic source. Basically, rapid urbanization leads to reduced infiltration rates and subsurface storage of water which increases input to floodwater. The rapid rise of urbanization had not been complemented with an associated increase in the efficient disposal of storm water, giving rise to increasing flooding problems. With the formation of the Drainage Department, over a couple of decades ago, the trend seems to be reversing.

Effects

Unlike larger agricultural countries in which floods also bring beneficial effects, such is not the case in Singapore. Historically, there have been most types of damages (including loss of human lives) associated with floods in Singapore, but recently it seems that flood damage in Singapore is more indirect and in the form of inconveniences rather than direct (like loss of human lives, property, etc). Among the indirect effects, landslides and disruption in road transport are most noteworthy.

Flood alleviation

Visitors to Singapore are generally quite amazed at the rapidity with which the stormwater disappears following some heavy rainstorms. This is basically the result of concerted effort of many government (and non-government) agencies, mainly the Drainage Department of the Ministry of Environment, which was established in 1972 (Foo, 1986) and which tries to control flooding in Singapore by following the legislation, mainly the "Water Pollution Control and Drainage Act, 1975".

Alleviating the problems of flooding in Singapore is practised both through structural (physical) and non-structural (administrative) adjustments. Among the former, inundation is prevented through decreased input of tidal water in the drains through tidal gates, and modifying output through quick and/or delayed/reduced discharge. An extensive network of concrete lined drains (a total of 571 km according to the Ministry of the Environment, 1990) attempts to remove the stormwater quickly. Guidelines for such drainage system are outlined by the Drainage Department (1991). The rational formula is used to compute the peak runoff for estimating the capacity of drains. For all major rivers and major/important installations (e.g. airports, tunnels) a recurrence interval of 50 to 100 years is chosen while for all "outlet drains and secondary drainage facilities" (Drainage Department, 1991) a recurrence interval of 5 years is selected in computing the maximum rainfall intensity values for the Rational formula. Drainage systems in all new developments are built with these guidelines. Many areas of Singapore which were developed before these guidelines were
established, have their drainage systems constantly being modified. Additional measures such as diverting stormwater from the flood-prone areas are also being adopted. Stormwater output is also modified through reduced or delayed discharge by storing water on the surface (mainly in reservoirs) or subsurface (through increased vegetation, infiltration, etc). In many cases several of these measures have had to be adopted in order to successfully alleviate the flood situation. Most notorious of such cases is the area adjacent to the lower reaches of the Bukit Timah canal. Several of these measures have been adopted during the last few decades (since 1930 according to Straits Times, 1990) to minimize frequent flooding in this valley and low-lying area; the last one involving, deepening and widening of the 2.2 km section of the older canal, constructing a 4.4 km diversion canal (including 2 km of tunnel), widening and improving of 2.5 km section of Kallang River, was completed in November 1990 with a cost of over S$240 million (over US$140 million) (The Straits Times, 1990; Ministry of the Environment, Annual Report, 1990). Inundation is also avoided by raising low-lying grounds, or through embankments and stilts, or through flood-proofing.

Among the non-structural measures legislative controls, flood relief operations, insurance, warning and forecasting are noteworthy. Many other agencies such as the Meteorological Services (providing forecasting facilities), Singapore Police Force, Public Works Department, media agencies (newspapers, radio, TV etc.) also assist during these measures.

Land-use planning and land zoning according to flood hazard, popular in many larger countries, can not be sufficiently practised in Singapore due to very limited available land area.

Minimizing the problems of flooding in Singapore has required a delicate balance between effective and efficient measures of flood alleviation and available resources such as land and public funds. It has also required careful analyses through multidisciplinary approach involving agencies familiar with the prevailing physical environment.

CONTROL OF FRESH WATER POLLUTION

Introduction

Fresh water from most sources in Singapore meets all the various quality standards. This has been made possible through concerted efforts of cleaning, legislation and maintenance by various government organizations. An evaluation of fresh water quality in Singapore from the following sources is summarized here: rainwater, fresh water in water courses (streams and drains), fresh water in water bodies (reservoirs), treated (piped) municipal water, waste water.

Rainwater

Rainwater over most parts of Singapore is acidic (i.e having pH values less than 5.6) but except for some pockets of areas where the pH of rainwater appears to be less than 5, most areas have pH values slightly over 5 (Rahman & Tan, 1985). This stems, aside from natural climatological causes, from a concerted effort by the government
of controlling (relocating, phasing out) industrial activities giving rise to acid rain. The Pollution Control Department (1990) of the Ministry of the Environment uses the "long term goals of WHO" and the "primary air quality standards of the US EPA" to assess the quality of ambient air in Singapore. All parameters monitored over a dozen locations in Singapore have been reported to be well within these two standards during the last decade.

**Fresh water in water courses and water bodies**

The quality of water in reservoirs and catchment areas is managed and monitored by the Public Utilities Board and outside these areas by the Pollution Control Department (and the Sewerage Department) of the Ministry of the Environment. Several legislative controls such as the "Water Pollution Control and Drainage Act, 1975" and the "Trade Effluent Regulations (TER), 1976" (and the amendment 1977) help these agencies safeguard the quality of water. Trade effluents from all industries have to meet these standard. There are three standards for the discharge of effluent: one for sewers, one for controlled water courses (i.e. water courses in catchment areas) and a third one for the others (Ong & Ng, 1983). There are also "water-borne Sewage Removal Fee" and fines for exceeding the TER. This is accompanied by the fact that 100% of the population "enjoys modern sanitation" (Ministry of the Environment, 1990). With the phasing out of many agricultural activities such as the pig farms, the streams which were receiving the wastes from the last remaining pigs have shown great improvement in quality and now support aquatic life (Pollution Control Department, 1990).

Both the Public Utilities Board and the Pollution Control Department of the Ministry of Environment monitor the water bodies (e.g. reservoirs) and the water courses (e.g. the drains and streams); the former in the catchment areas (47 streams and 13 reservoirs) and the latter in non-water catchment areas (17 streams), through an extensive network of sampling points and regular sampling and testing. These agencies have been reporting the quality of the water in catchment areas to be good and outside the catchment areas to be improving. The author's own tests have shown that the water in (the water bodies of) catchment areas meets most of the drinking water standards set by WHO. Obviously the quality of raw water from the unprotected catchments would be poorer than that from the protected catchment. Generally the colour, turbidity, suspended solids and organic content of raw water from the unprotected catchments, and the dissolved solids in the estuarine reservoirs are higher (Wong & Tng, 1988).

**Drinking (municipal piped) water**

While the conventional treatment processes (coagulation/ flocculation, filtration, disinfection and conditioning using chlorine, lime and fluoride) are used for treating the water collected from the protected catchments, additional processes (pre-treatment with chlorine, ozone, and/or potassium permanganate and hydrated lime, and post-treatment with ozone) are adopted to treat the raw water from the unprotected catchments (Wong & Tng, 1988). The treated water is either stored in (covered) service reservoirs, often built on higher grounds, or transferred to covered concrete
tanks from where the water is pumped to the consumers. One hundred percent of the population is supplied with metered piped water meeting the WHO standards. There are as yet no local standards and the International (water quality) Standards for Drinking Water set by the WHO are used as the guideline (Public Utilities Board, 1979). The quality in the distribution network is also regularly monitored through sampling (at treatment plants, storage reservoirs, tanks, pipes and consumer outlets, etc.) and testing (Yip, 1985).

Waste water and recycled waste water

All waste waters in Singapore are collected and treated before being discharged into the sea or the river mouth, and the treated effluent quality from all sewage treatment works meets stringent standards of 20 mg l\(^{-1}\) of BOD and 30 mg l\(^{-1}\) of suspended solids) (Ministry of the Environment, 1991). Some effluent is further treated for use as industrial water to conserve potable water. This was started by the Jurong Town Corporation well over two decades ago (Kwok, 1986). The treated sewage effluent (from Ulu Pandan Sewage Treatment Works) is subjected to further treatment at the Jurong Industrial Waterworks before being sent to consumers. Even at its best this recycled waste water contains suspended and dissolved impurities well above those recommended by WHO for drinking water. This recycled water is therefore used by industries (for cooling, manufacturing, etc.), by Parks and Recreation Department (for watering the vegetation), and by some apartments (for toilet flushing). In addition several industries, and hotel and apartment complexes utilize in-house recycled waste water for various non-potable purposes.

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